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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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☒ *Additional inventors are being named on the* 2nd *separately numbered sheets attached hereto*

TITLE OF THE INVENTION (500 characters max)

A Power-flow Based Standardized Modeling and Simulation Method for Complex System

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

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Respectfully submitted,

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A Power-flow Based Standardized Modeling and Simulation Method for Complex System

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Abstract: This paper presents a power-flow based standardized modeling method and automatic simulation procedure for complex engineering system composed of mechanical, electrical and hydraulic subsystems. Three kinds of conventional modeling methods, bond-graph, functional-model and block-diagram, are briefly summarized first. Then a standardized modeling and simulation method (SMSM) is presented and implemented. Due to take advantages of bond-graph, functional-model and block-diagram in Simulink of commercial code of Matlab, SMSM blends of standardized element units, effort-flow based graphic frame, routinized modeling procedure and automatic simulation without need to writing out system mathematic equation. Finally, three types of mechanical systems with typical linear and nonlinear performances are studied. Comparisons of modeling procedure and graphic models of SMSM, bond-graph method and functional-model method clearly demonstrate differences and relationships among those methods. Simulational results of the SMSM models, which meets well with the numerical results of their mathematic equations and functional-models, verify the practicability and effectiveness of SMSM. SMSM to conveniently create highly readable, unified and hierarchical models for multidisciplinary systems and to efficiently carry out automatic simulation process provides engineers with an effective modeling and performance prediction technique for large-scale product design and development.

Key words: Modeling, Simulation, Power-flow, Functional model, Block diagram, Bond graph

1 Introduction

Nowadays engineering systems are becoming increasingly complex to accomplish more demanding tasks in more efficient ways, which usually contains mechanical, electrical and hydraulic subsystems that interact in complex ways. In design and development of such multidisciplinary system, prediction and analysis of its performance are very important to ensure design quality, shorten product design cycles, reduce development cost and explore optional schemes especially in concept design stage. With increasing complication of engineering system, CAE (Computer Aided Engineering) as a powerful tool to investigate performance of complicated systems becomes particularly necessary. Unified modeling approach to conveniently obtain legible and hierarchical models of multidisciplinary systems is the primary to CAE system technology, and automatic derivation of system mathematic equation and automatic system performance simulation largely improve efficiency of CAE technology.

Unified modeling method and automatic numerical simulation have been studied for many years. Graphic modeling method, as a bridge between physics and mathematics descriptions of engineering

system, is one solution to get a unified model legible for describing multidisciplinary systems in a standard way and to enable engineers in different fields to understand the standardized model without knowing deep theories in other fields. Power-flow based graphic modeling approaches such as bond-graph method developed by Ronald C. Rosenberg and Dean C. Karnopp [1-7] and functional-model proposed by Sumida Shizuo, Nagamatu Akio [8-19] have the capabilities to obtain unified model for multidisciplinary system and to automatically generate mathematic equation directly from graphic model. Block-diagram oriented tools of Simulink in the commercial code of Matlab [20], Auto-code Generator in the commercial code of Beacon and SystemBuilder in the commercial code of MATRIXx express mathematic equation in a graphic way and perform automatic simulation, which are especially useful in design and build of control system.

In this paper a practical and reliable Standardized Modeling and Simulation Method (SMSM in short) based on power-flow is proposed, which takes advantages of bond-graph, functional-model and block-diagram model in Simulink to establish standardized model and accomplish automatic simulation for complicated system. As applications of this modeling technique, several typical linear and nonlinear mechanical systems are numerically simulated. The analysis results as well as the effectiveness and efficiency of SMSM are verified. This method can be applied into some other systems such as electrical, hydraulic and their mixed systems, and also can be combined with other modeling and design technologies such as finite element method, experimental statistics method to enhance capability of CAE system technology.

2 Comparisons of Conventional Modeling Methods

Dynamics of physical system stems from power exchange among its components described as power-flow. Power statement of the product of a pair of effort and flow in various systems shows striking analogies, as shown in Table 1. Bond-graph and functional-model are developed on the basis of the analogy of power descriptions and power conservation, in which effort and flow are used as state variables to connect various systems into a unified form. In this section three kinds of modeling

Table 1 Standardized bond-variables and elements in bond-graph

	Mechanical system		Electrical system	Hydraulic system
	Translatory system	Rotational system		
Effort	Force: F *(N)*	Torque: τ *(N·m)*	Voltage: e *(V)*	Pressure: P *(Pa)*
Flow	Velocity: V *(m/s)*	Angular velocity: ω *(rad/s)*	Current: I *(A)*	Volume flow rate: Q *(m^3/s)*
Momentum of impulse	Momentum: P *(N·s)*	Angular momentum: H *(N·m·s)*	Flux linkage: λ *(Wb)*	Integral of pressure: *Pp(Pa·s)*
Displacement	Displacement: x *(m)*	Angular: θ *(rad)*	Charge: q *(C)*	Volume: V_l*(m^3)*
Power	$F{\cdot}V$ *(W)*	$\tau\cdot\omega$ *(W)*	$e{\cdot}I$ *(W)*	$P{\cdot}Q$ *(W)*
Inertia element	Mass: m *(Kg)*	Inertia: I *(m^2)*	Inductor: L *(Wb/A)*	Fluid inertia: *I(Kg/m^4)*
Capacitor element	Spring stiffness: K *(N/m)*	Coil spring stiffness: K *(N·m /rad)*	Capacitor: C *(C/V)*	Fluid capacitor: C *(m^5/N)*
Resistor element	Resistance: R *(N·s /m)*	Resistance: R *(N·m·s /rad/)*	Resistor: R *(V/A)*	Fluid resistance: R *(N·s/m^5)*
1-junction	Common-velocity	Common-angle velocity	Series electrical connection	Common- volume flow rate
0-junction	Common-force	Common-torque	Parallel electrical connection	Common-pressure
Active port	*Se*: force source *Sf*: velocity source	*Se*:torque source *Sf*: rational velocity source	*Se*: voltage source *Sf*: current source	*Se*: pressure source Sf: volume flow rate source

methods, bond-graph, functional-model and block-diagram in Simulink, are reviewed and compared.

(1) Bond-graph modeling method

Bond-graph is a highly organized schematic modeling method using generalized symbols or elements to represent almost all applicable types of lumped-parameter systems. Pictorial model of bond-graph, for example, the bond-graph model of Fig. 4 (b), is composed of line called bond and nine basic bond-graph elements grouped into four groups as shown in Table 1: the dissipation field of Resistor element; the storage fields of Inertia element and Capacitor element; the general junction-structure groups of 0-junction and 1-junction, transformer (*TF*) and gyrator (*GY*); the source fields of active ports (*Se* and *Sf*).

Bond connecting element with junction marks a power connection with bond-variables of effort and flow written in the upper and lower of the bond and a half arrow pointing in the direction of power flow. A single mark of causal stroke on a bond indicates input-output relation between effort and flow at each port, which flow in opposite directions. Each passive 1-port element of *R*, *C* and *I* represents a constitutive law between bond-variables of effort and flow or their time integrals. *R* dissipates power from system, and *C* and *I* storage power. 1-junction also named as common flow junction has the special nature that the flows on the bonds attached to it are equal and the algebraic sum of all efforts attached to it is zero. On the contrary, 0-junction namely common effort junction possesses the special nature of that the efforts on the bonds attached to it are equal and algebraic sum of all flows attached to it is zero. 0-junction is regarded as the dual junction of 1-junction in the sense that the roles of effort and flow are reversed. Ideal 2-port element of *TF* relates effort to effort and flow to flow by a proportional dimensionless coefficient called modulus of the transformer. While ideal 2-port element of *GY* relates the effort at one port to the flow at the other by a dimensional parameter of effort divided by flow. All Junction 0,1, *TF* and *GY* are power conservation. Sf and Se supply power into Bond-graph.

With these generalized elements and their built-in analogy in different systems, bond-graph modeling process can be performed in an orderly way as shown in Table 2, which leads to economy of thought and helps engineers to rapidly establish an organized dynamic analysis model for

Table 2 Bond-graph modeling procedure

Mechanical system	1. Simplify physical system into a lumped-parameter model. 2. Establish one 1-junction for each velocity. 3. Connect *I* to 1-juncions and insert 0-junction between a neighboring 1-junction pair. 4. Connect *C* and *R* to 0-juncions. 5. Connect 0 and 1-junctions directly or using TF or GF if necessary. 6. Insert force and velocity sources appropriately. 7. Assign half arrows and causal stroke to bond. 8. Simplify the graph.
Electrical system	1. Establish circuit construction. 2. Establish a 0-junction for each node with a distinct voltage in the circuit. 3. Insert each 1-port element between a neighboring pair of 0-junctions by attaching the 1-port to a 1-junction and then bonding the 1-junction to two neighboring 0-junctions. 4. Assign half arrows and causal stroke to bond. 5. Choose a particular node to be ground and simplify the graph.
Hydraulic system	1. Simplify fluid line into a distributed-parameter system. 2. Establish a 0-junction for each pressure. 3. Attach *C* element to 0-junction. 4. Attach *I*, *R* or *TF* to 1-junction and connect the 1-junctions between two neighboring 0-junctions. 5. Simplify the graph.

complicated system. Another remarkable feature of bond-graph is that standard system state-space equation can be automatically derived in an orderly way from a given bond-graph diagram for subsequent numerical analysis.

(2) Functional-model method

Functional-model method composed of element unit and operation is another kind of power-flow based modeling method, which demonstrates physical function of system and power-flow transmitted in system in a visual way and enables engineers in various specialties to easily understand and collaborate with each other [8]. State variables of flow and potential, whose product becomes power as that of flow and effort in bond-graph, construct main graphic frame as shown in Fig.2 (b). Visualized element units in various systems as shown in Table 3 explicitly explain the basic constitutive law between flow and potential. Expansion and unification of functional-models make it easy to set up hierarchical model from small-scale to large-scale subsystem, to assemble machine from parts to total product or disassemble machine and exchange parts [12]. Functional model can cooperate with mechanism model to control parameter and modeling nonlinear physical property [13]. Furthermore, system state-space equation can be derived automatically from diagram of functional-model, and system performance simulation can be performed by numerical computation of the mathematic equation.

(3) Block-diagram method

The block-diagram model in Simulink of commercial code Matlab is reviewed in this section. Simulink block-diagram is a pictorial model to represent a known mathematical model of a dynamic system, which consists of directed lines and blocks interconnected by lines. Each line represents a single variable flow and connects between block output and block input. Each type of block represents a particular relationship between its input and output variables. A block-diagram can contain any number of instances of any type of block. A simple way to create a block diagram is to start with a system mathematic equation. Nonlinear block library helps to establish nonlinear model. The capabilities to group blocks into subsystem and to create new block by using *S*-Function allow a hierarchical model to be built using both top-down and bottom-up approaches for a complex system with complicated linear and nonlinear performances. Moreover, subsequent simulation on block diagram can be automatically performed by Simulink solver using numerical computation methods in Matlab without writing out system equation implied in block diagram [20].

(4) Comparison of modeling methods

Unified modeling approaches of bond-graph and functional-model are visualized descriptions for lumped-parameter physical model on the basis of power-flow, which have the similar advantages as follows:

- General symbols are used to model multidisciplinary system in a unified format, and graphic models involved different energy type demonstrate striking analogies.
- Physical function and power interchange between components of a system are illustrated in a pictorial way.
- Standard form of state-space equation can be automatically derived from graphical model.

Due to these similarities, a bond-graph diagram can be routinely converted into an equivalent functional-model by replacing each bond-graph element into equivalent functional-model unit and

Table 3 Element unit in various dynamic system

		Translatory system	Rotational system	Electrical system
Functional model	Inertia unit	Mass unit: (Force) 1/M (Velocity)		Inductance unit: (Voltage) 1/L (Current)
	Capacitor unit	Stiffness: (Velocity) K (Force)		Capacitance unit: (Current) 1/C (Voltage)
	Resistor unit	Damping unit: (Velocity) Cm (Force)		Resistance unit: (Voltage) 1/R (Current)
SMSM	Inertia unit	Mass unit: M Mass-unit its detail subsystem (Force) 1 In1 1/Mass 1 Out1 (Velocity)	Inertia unit: J Inertia-unit its detail subsystem (Torque) 1 In1 1/J 1 Out (Angle velocity)	Inductance unit: L Inductance-unit its detail subsystem (Votage) 1 In1 1/L 1 Out1 (Current)
	Capacitor unit	Stiffness unit: K Stiffness-unit its detail subsystem (Velocity) 1 In1 K 1 Out1 (Force)	Stiffness unit: Kr Rotational stiffness-unit1 its detail subsystem (Angle velocity) 1 In1 Kr 1 Out1 (Torque)	Capacitance unit: C Capacitance-unit its detail subsystem (Current) 1 In1 1/C 1 Out1 (Voltage)
	Resistor unit	Damping unit: C Damping-unit its detail subsystem (Velocity) 1 In1 C 1 Out1 (Force)	Damping unit: Cr Damping-unit its detail subsystem (Torque) 1 In1 Cr 1 Out1 (Angle velocity)	Resistance unit: 1/R Resistance-unit its detail subsystem (Voltage) 1 In1 1/R 1 Out1 (Current)

operation according to the following transformation rule:

1. Each bond in bond-graph corresponds to a pair of directed signals of flow and effort in functional-model.
2. 0-junction in bond-graph denotes a pair of operations in functional-model that the flows are summed and effort is distributed. And 1-junction is treated in similar way that efforts are summed and flow is distributed.
3. Causal mark of one bond in bond-graph indicates the directions of corresponding flow and potential in functional-model.
4. *TF* is replaced by proportionally connecting two pairs of effort and flow with a coefficient respectively. *GY* is replaced by relating the effort at one port to the flow at the other with a coefficient respectively.
5. Effort source in bond-graph corresponds to an input potential signal in functional-model, and flow source in bond-graph corresponds to an input flow signal in functional-model.

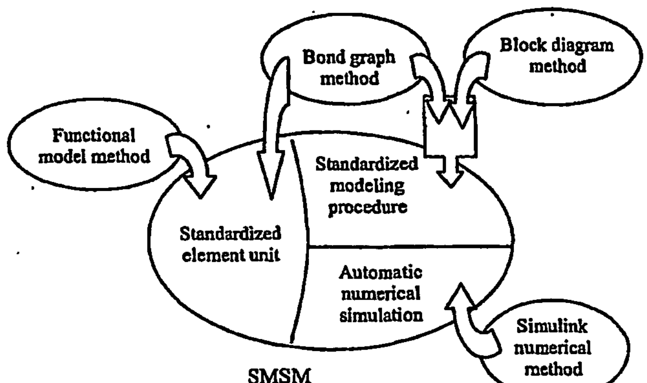


Fig. 1 Relationship among various modeling and simulation methods

Table 4 SMSM modeling procedure

Mechanical system	1.	Simplify physical system into lumped-parameter model.
	2.	Establish a pair of operations of force sum and velocity distribution for each velocity. Connect element unit I to its proper force and velocity pair.
	3.	Insert a pair of operations of velocity sum and force distribution between the two neighboring pairs of force sum and velocity distribution if there are C and R. Then, connect C and R to this pair of operation properly.
	4.	Connect two pairs of effort and velocity together by multiplying a coefficient respectively if necessary.
	5.	Establish nonlinear block using S-Function and subsystem tools.
	6.	Insert force and/or velocity source signal generators appropriately.
	7.	Simplify the graph by grouping some blocking into subsystem.
Electrical system	1.	Establish circuit construction.
	2.	Establish a pair of operations of current sum and voltage distribution for each node with a distinct voltage in the circuit.
	3.	Insert a pair of operations of voltage sum and current distribution between two neighboring pairs of currents sum and voltage distribution. Connect element unit to this the pair of operation.
	4.	Insert voltage and/or current source signal generators appropriately.
	5.	Simplify the graph by choosing a particular voltage node to be ground.
Hydraulic system	1.	Simplify fluid line into distributed-parameter system.
	2.	Establish a pair of operations of volume flow rate sum and pressure distribution for each pressure.
	3.	Attach C to the operation of volume flow rate sum and pressure distribution.
	4.	Insert a pair of operation of pressure sum and volume flow rate distribution between two neighboring pairs of volume flow rate sum and pressure distribution.
	5.	Attach element units of I and R to the pair of operations of pressure sum and volume flow rate distribution.
	6.	Connect two neighboring pairs of volume flow rate and pressure together by multiplying a coefficient respectively if necessary.
	7.	Insert pressure and/or volume flow rate source signal generators appropriately.

Even though bond-graph and functional-model have similarity and can be converted each other, they have their own properties. Bond-graph requires special learning due to its special symbols, which make its graphical models are not easily accepted by engineer. On the contrary, functional-model uses ordinary engineering symbols, so it can be more easily to be understood and be applied in engineering. Some nonlinear problems are difficult to be described by bond-graph, but they can be conveniently considered in functional-model by adding mechanism-model.

Comparing with bond-graph and functional-model made up of element units, block-diagram model in Simulink built by mathematic symbols has much difficulty in modeling establishment directly from physical system. Thus, block-diagram describing mathematical model in a clear way is hard to demonstrate physical function and power-flow of system.

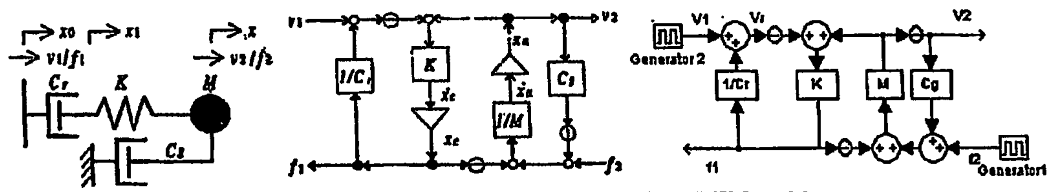
3 Standardized modeling and simulation method

SMSM is developed by taking advantages of bond-graph, functional-model and block-diagram as shown in Fig. 1. The standardized element units are subsystem blocks built by Simulink library blocks as shown in Table 3, which adopt the concepts of bond-graph element and functional-model element symbols to represent element functional characteristics in various systems between state variables of effort and flow in a simple way. The proposed standardized modeling procedure directly modeling physical system is shown in Table 4, which combines the modeling procedure of bond-graph with the transformation rule converting bond-graph into functional-model. The main graphic frame of SMSM model is constructed by flow and effort as flow and potential in functional-model, and can be built in hierarchical way by creating subsystem block. Nonlinear performance can also be conveniently modeled by creating nonlinear subsystem like the mechanism

model in functional-method. Hence, SMSM is a power-flow based modeling approach, which helps to conveniently build up understandable and unified model for multidisciplinary system and provides insight into how a model is organized and how its parts interact. Automatic numerical simulation can be implemented on SMSM graphical model by Simulink solver with no need to write out system equation and make program to calculate the equation. Therefore, users are able to concentrate on modeling decisions without being saddled with algebraic drudgery and burden for making numerical computation program.

SMSM has highly flexibility. It can be established directly from physical model, or converted from functional-model and bond graph model. Block-diagram set up from mathematic equation or physical models such as electrical circuit can be built into hierarchical subsystem as a part of SMSM model. Model change can also be conveniently performed on the existed graphical model. Moreover, SMSM simulation process is readily incorporated with other analysis and design methods of dynamic system by using Matlab toolboxes, for example experimental analysis method, optimization design method.

To sum up, SMSM collects the advantages of highly readability, quick establishment, explicit function and power-flow description, wide applicability and automatic simulation for numerical study of complex systems.

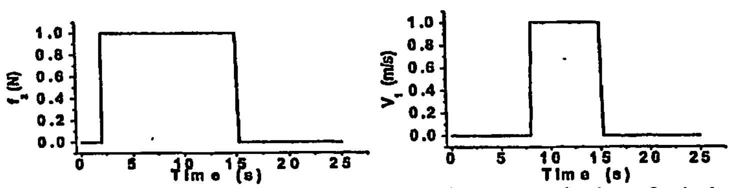


(a) Structural model (b) Functional-model (c) SMSM-model

Fig.2 Models of SDOF Mechanical System

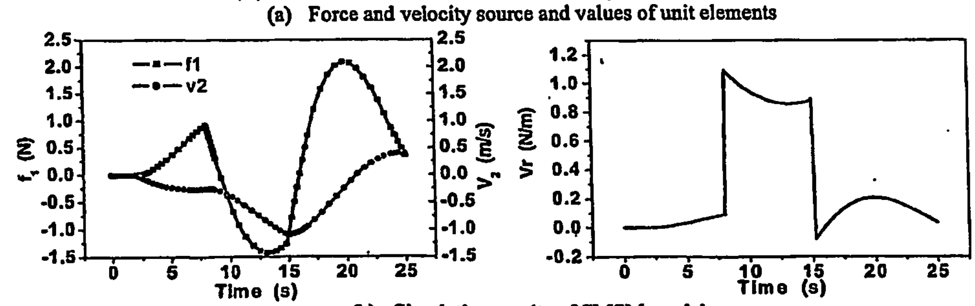
4 Applications

Several typical mechanical systems are studied to demonstrate SMSM modeling and simulation



M	10 *Kg*
K	5.0 *N/m*
Cr	10 *Nsec/m*
C_r	1.0 *Nsec/m*

(a) Force and velocity source and values of unit elements



(b) Simulation results of SMSM-model

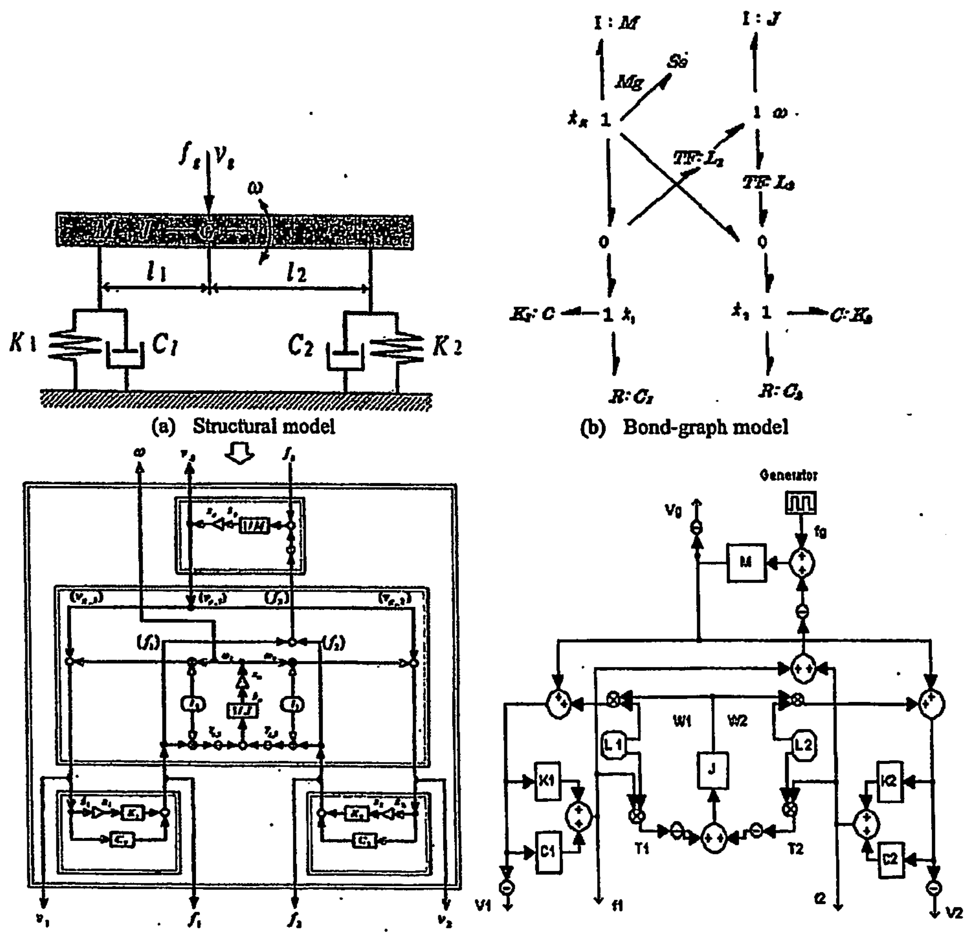
Fig.3 Simulational results of SDOF mechanical system

procedure. Comparisons of functional-model, bond-graph model and SMSM-model are also

presented. These examples are kept simple enough to show abilities of the proposed approach in solving linear and nonlinear problems. Validity and practicality are illustrated by comparisons of simulational results.

(1) A SDOF (Single Degree of Freedom) mechanical system

As shown in Fig. 2 (a), this mechanical system is composed of a mass, a spring and two dashpots. The functional-model [8] and SMSM-model shown in Fig.2 (b) and (c) are similar. It is obvious that the SMSM-model can illustrate function of each element unit and direction of power-flow as the functional-model does. However, the SMSM graphical description is more readible and simple than that of the functional-model. The SMSM-model can be established by converting the functional-model according to the transformation rule introduced in the last section or directly set up from the system mechanism model according to the standard modeling procedure shown in Table 4. The simulation results shown in Fig. 3 (b) under the force and velocity sources shown in Fig. 3 (a) meet with the numerical results of system state-space equation. Simulation of SMSM-model can be performed more conventiently by simulink solver than making numerical computational program as



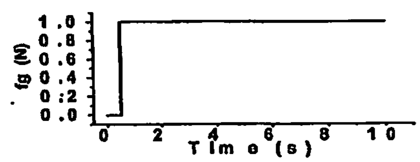
(a) Structural model
(b) Bond-graph model
(c) Functional-model
(d) SMSM-model
Fig.4 Models of suspended body

functional-model method did.

(2) Suspended body

A typical vibration problem show in Fig. 4 (a) is a suspended body, which is assumed to vibrate in small angular and translational motion in the plane with neglecting horizontal motion. Its various models are shown in Fig. 4 (b), (c) and (d).

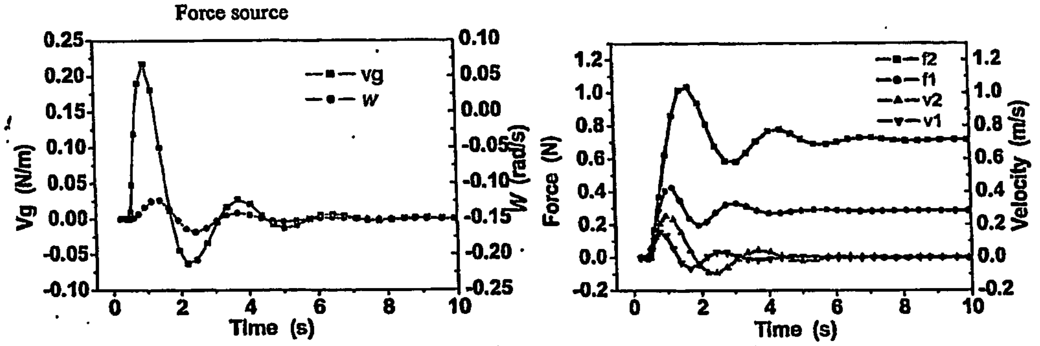
SMSM-model shown in Fig. 4 (d) can be tranformated from bond-graph model of Fig. 4 (c) and functional-model of Fig. 4 (b). It can also be directly established from the structural model of Fig. 3 (a) as the following steps according to the modeling procedure shown in Table 4. Step 1: establish four pairs of velocity-force frames, v_g and ω for the rigid body and $\dot{x}_1$ and $\dot{x}_2$ for the suspension; Step 2: attach element units of K, C and M to their corresponding velolcity-force frams; Step 3: connect the four velocity-force frames together by sum and distribution operations and



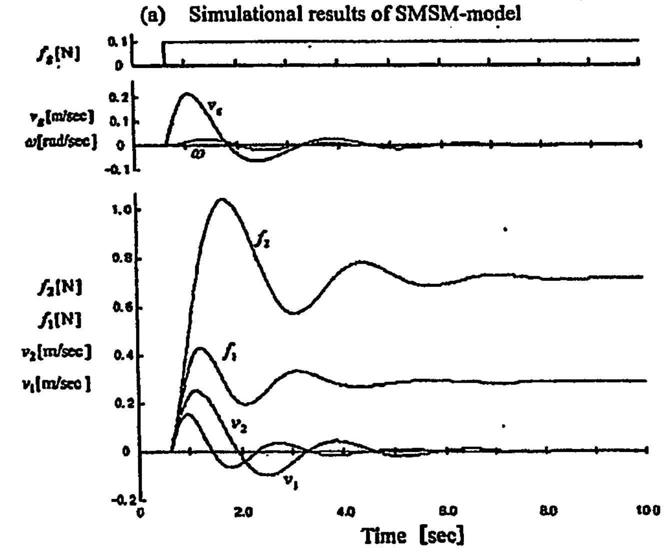
Force source

Values of unit elements

M	*1.0 Kg*	C_1	1.0 $N\cdot s/m$
J	*15 Kg/m²*	C_2	1.0 $N\cdot s/m$
K_1	5 Kg	D_1	-5.0 m
K_2	5 Kg	D_2	2.0 m



(a) Simulational results of SMSM-model



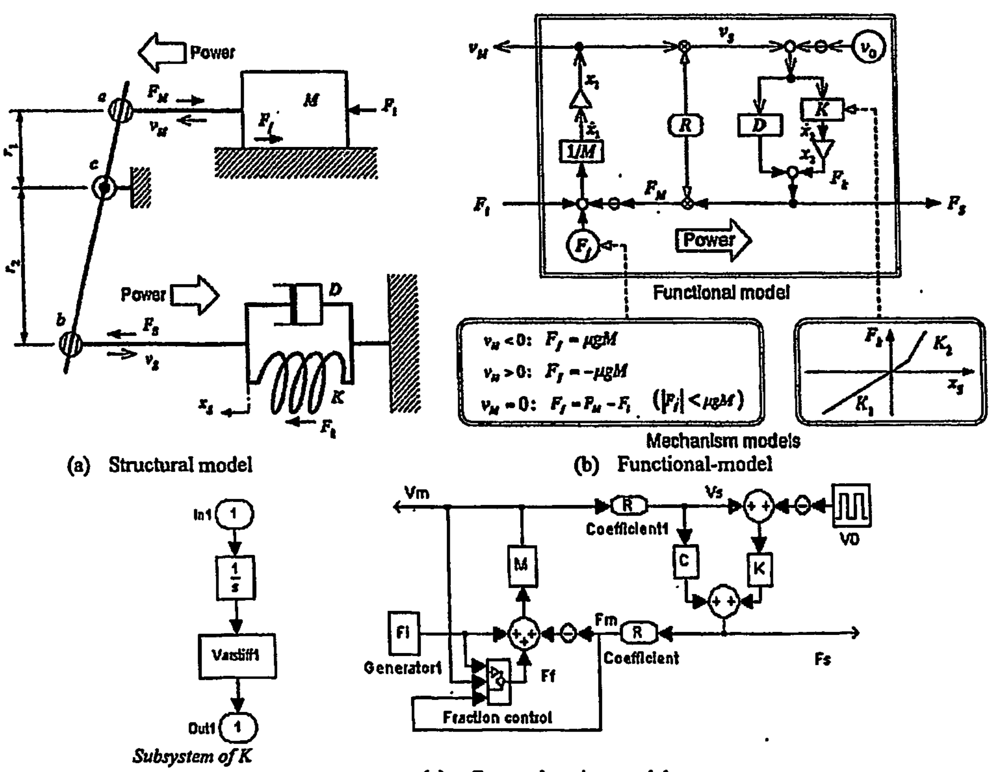
(b) Simulational results of functional-model

Fig.5 Simulational results of suspended body

transformation coefficient blocks according the relationships among them: the transformation coefficience blocks of L_1 and L_2 as shown in Fig. 4 (d) connect translatary subsystem with rotational subsystem in the same way as *TF* shown in Fig. 4 (b), and the operations of sum flow of $-v_1$ *and* $-v_2$ and effort distribution of f_1 and f_2 in Fig. 4 (d) is eqivalent to the 0-junction in bond graph of Fig. 4 (b) respectively. The simulation results of SMSM model under the force source of f_g are demonstrated in Fig. 5 (a), which is agreeable with the simulation results of functional-model shown in Fig. 5 (b) in Ref. [9] and the numerical results of system state-space equation.

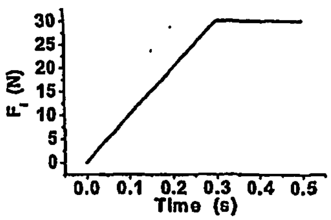
(3) A nonlinear mechanical system

A nonlinear mechanical system with typical material and friction nonlinearities as shown in Fig. 6 (a) are investigated. In SMSM-model shown in Fig. 6 (c), the two-stage spring stiffness is modeled by a subsystem *K*, in which a *S*-function of *Varstiff1* is programmed to control the stiffness property shown in the mechanism model of Fig. 6 (b). Friction between *M* and ground is divided into two stages, one is static-friction when *M* doesn't begin to move and the other is coulomb dynamic-friction proportional to the press upon the slide surface when *M* slips on ground. Nonlinear friction is modeled by another subsystem of friction control shown in Fig. 6 (c). Power-flow transformation through lever is described as two transformation coefficient blocks of *R* multiplied to velocity and force respectively. The simulation results under the force source of F_l are demonstrated in Fig. 7 (a), which is agreeable with the simulational results of functional-model shown in Fig. 7 (b). in Ref. [10] and the numerical results of system state-space equation. Thus, it is very convenient to built nonlinear model and carry out numerical simulation by using tools in Simulink.



(c) Comprehensive-model

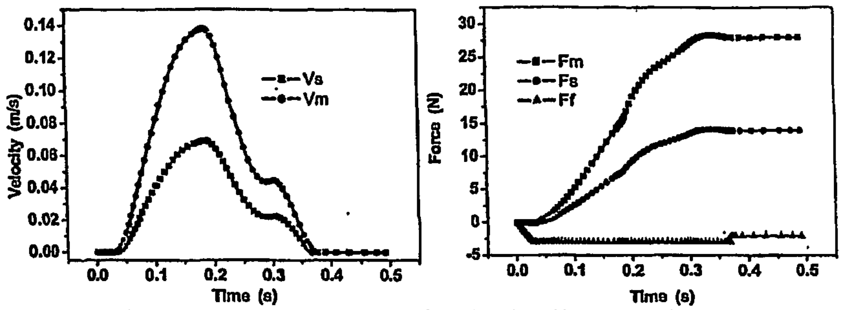
Fig.6 Models of a nonlinear mechani



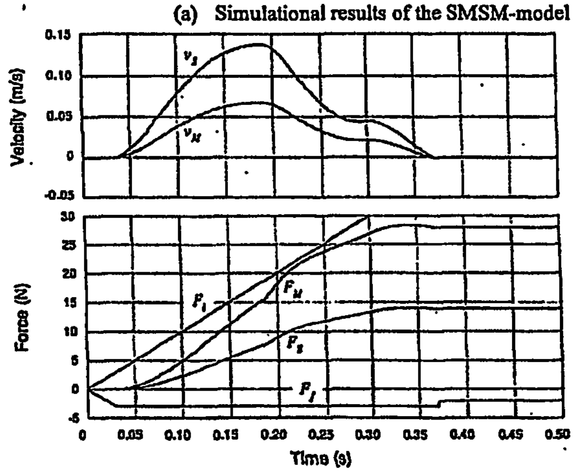
Force source

Values of unit elements

M		3 Kg	D	20 $N \cdot s/m$
r_2/r_1		2.0	V_0	0 m/s
K	K_1 ($F_k \leq 5N$)	400 N/m	μ	0.1
	K_2(F_k>$5N$)	800 N/m		



(a) Simulational results of the SMSM-model



(b) Simulational results of the functional-model

Fig.7 Simulational results of the nonlinear mechanical system

5 Conclusion

Unified modeling approach is important to performance simulation for complex system. In this paper, a comprehensive modeling and simulation method of SMSM based on power-flow is presented. This method is time saving and convenient for modeling a complicated system due to its advantages of standardized element unit, effort-flow based graphic frame, routinized modeling procedure and automatic simulation process. From the simulation results of several mechanical systems with typical linear and nonlinear properties, the effectiveness and practicability of the proposed method are verified. The success of this approach is that it takes advantages of bond-graph, functional-model and block-diagram in Simulink by blend of modeling procedure and automatic computation process. The proposed modeling techniques and simulation analysis method allow to creative a highly readable, unified and hierarchical model in a orderly way for a multidisciplinary engineering system composed of mechanical, electrical and hydraulic systems interacting in complex ways and effectively perform automatic simulation analysis on computer. The presented

method can also conveniently combine with other types of analysis methods such as finite element analysis method and product design methods to enhance capability of CAE system technology for complicated engineering problems.

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